Optimizing Fusion Performance in a Tokamak: MHD, H-Mode, and AT

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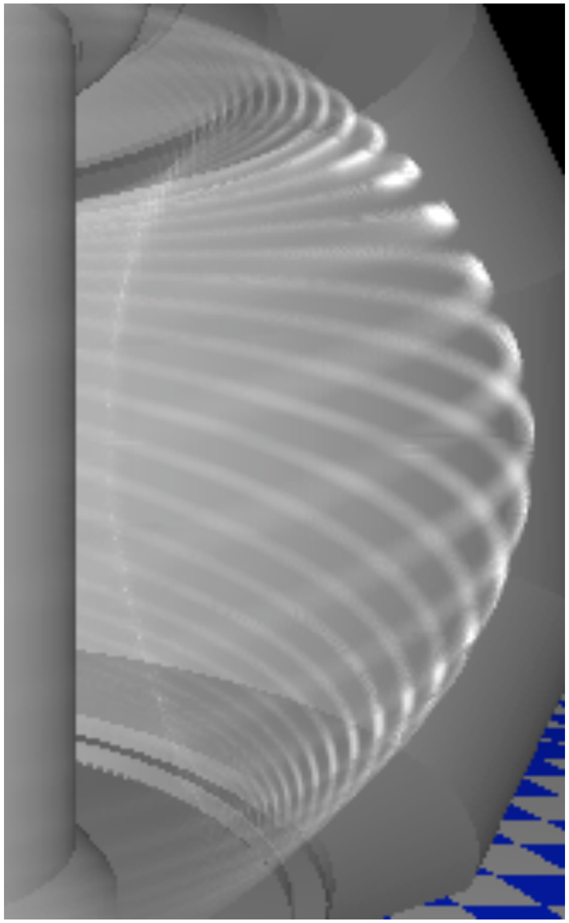
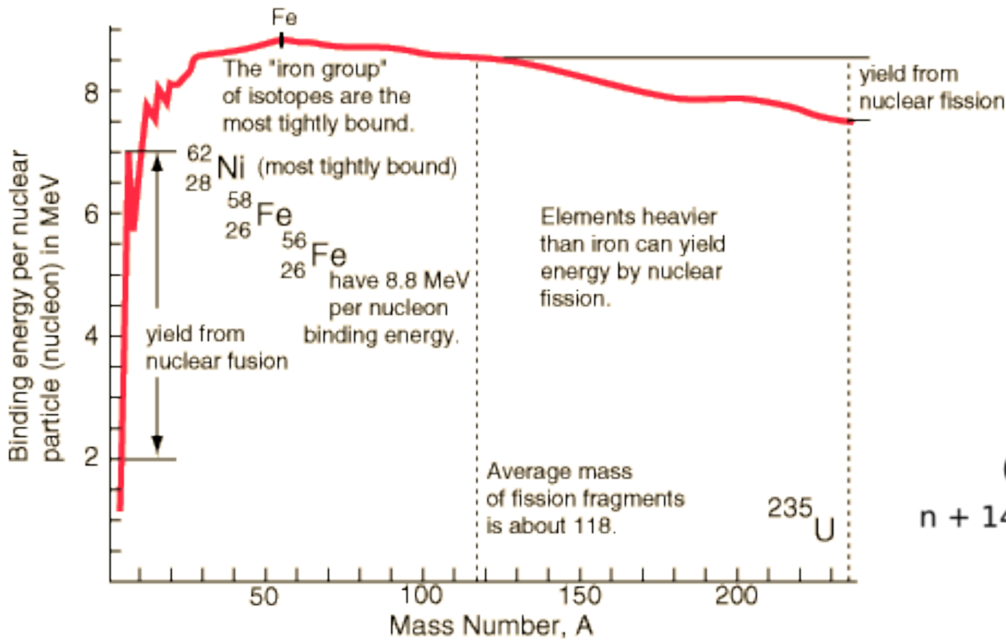
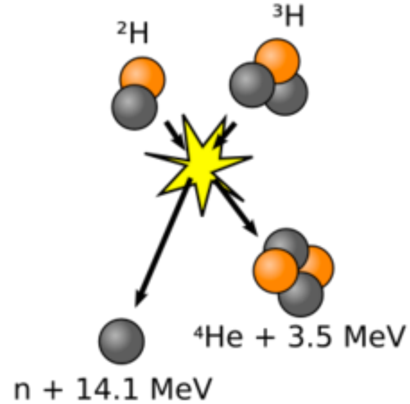


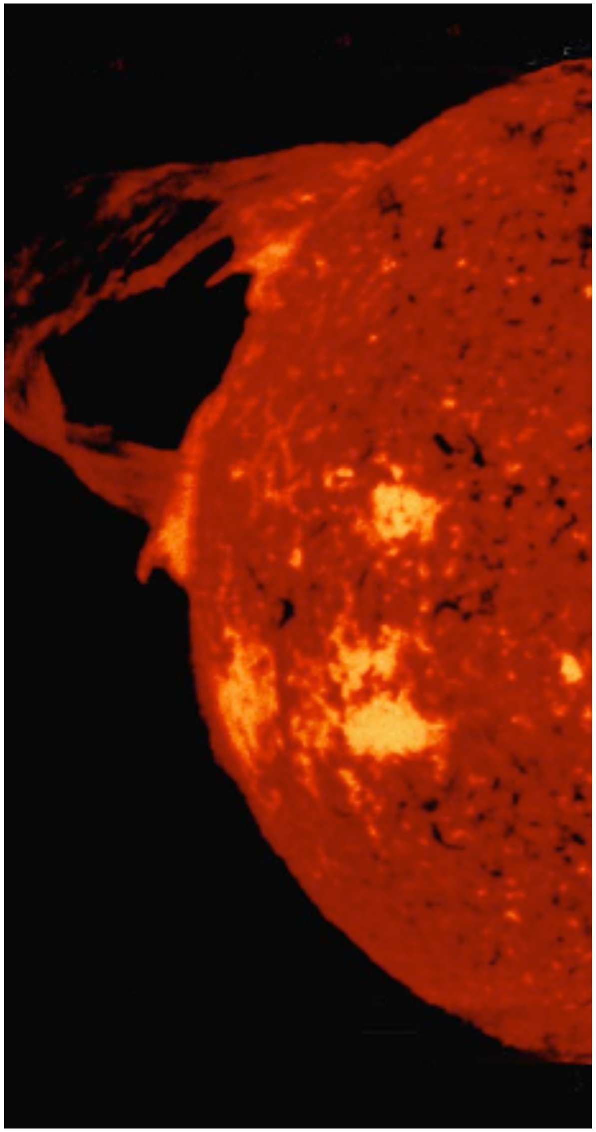
Acknowledgments: D. Brennan, DIII-D team

LANL Summer Student Seminar
27 July 2006

Fusion Powers the Sun and Stars







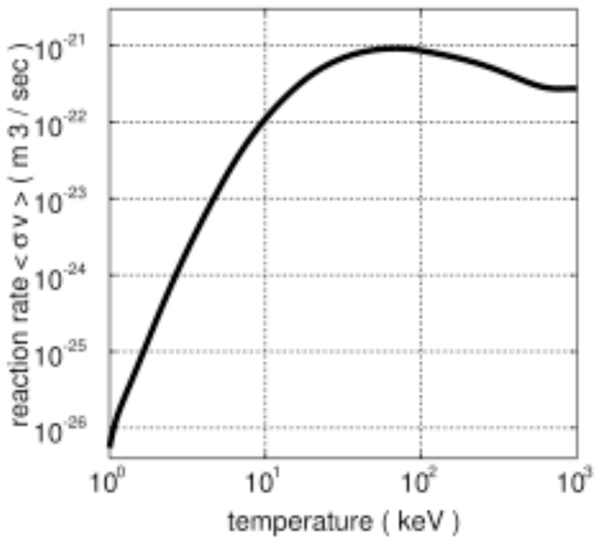
- **Light nuclei release substantial energy when fused into heavier nuclei**
  - Proton-proton and CNO fusion cycle in stars
  - D-T reaction promising for fusion energy
- **Essentially limitless supply and potentially benign environmental impact make fusion energy very appealing, despite challenges**

Basic Physics of Fusion

- **Fusion reaction rates peak at high energy (D-T ~70keV=~800 million C)**
  - High energy needed to overcome Coulomb repulsion
  - Even at peak fusion rate, cross section for fusion << Coulomb scattering
    - Beam-target can produce fusion, but very difficult to produce net energy gain

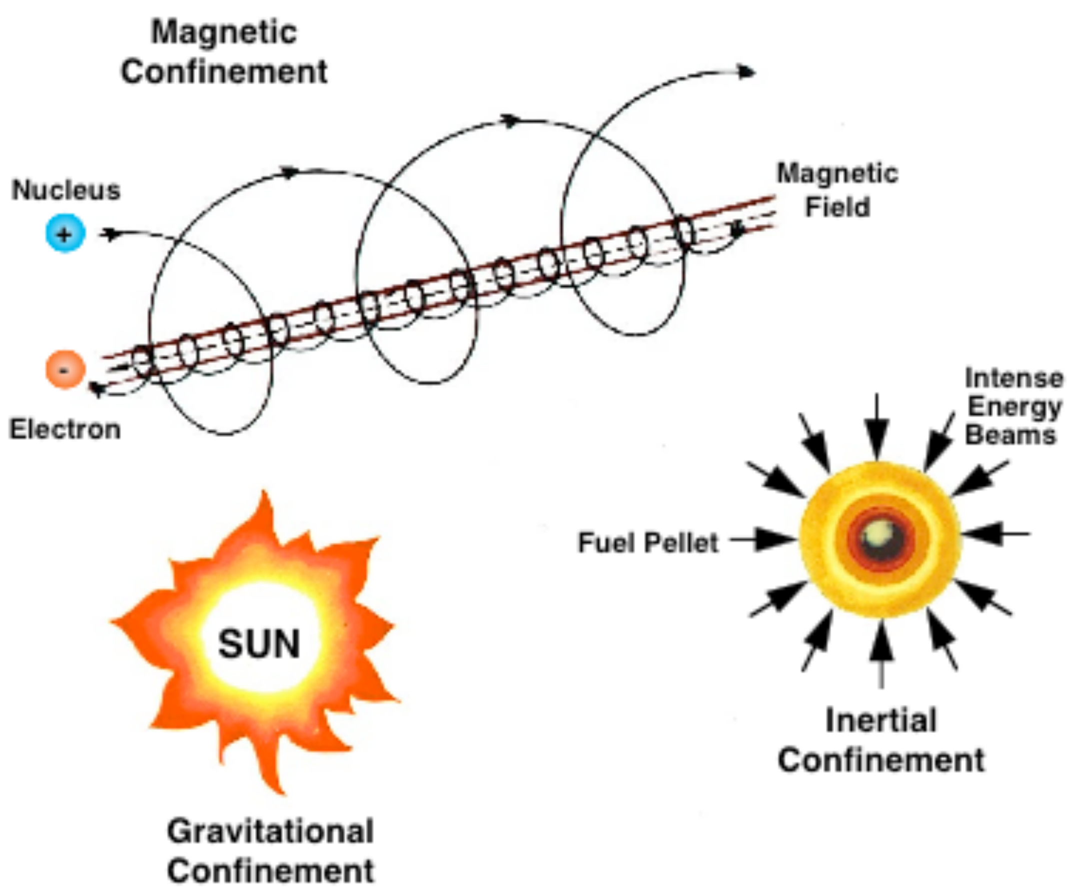
⇒ **Ions must be *confined* for several collisions**
  - Distribution will be approximately thermal, or Maxwellian (thermonuclear)

⇒ **At the necessary temperature, you have a *plasma***
  - T >> ionization energy



- **Much of the physics involved in fusion is high temperature plasma physics**
  - Broad applications across many phenomena
  - > 99% of universe is plasma, rocky planets are exceptions (lightning, fluorescent lights)

Approaches to Confining a Hot Plasma



- **Also other variations such as electrostatic, MTF**
- **Here we'll focus on magnetic confinement**
  - Ions follow B field lines, orbit with

    $$\rho_c = v_T / \Omega_c = c\sqrt{Tm} / eB$$

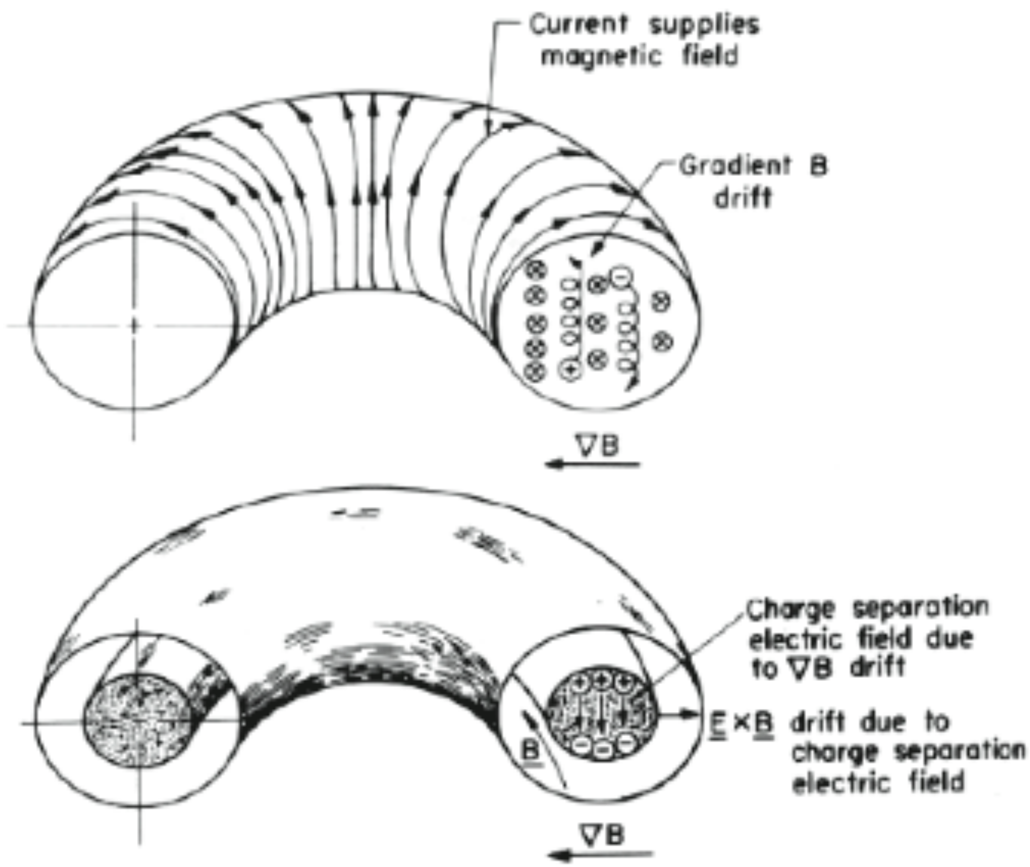
  - Must close ends, magnetic mirror or…

Toroidally Closed Magnetic Field Requires Helicity for Particle Confinement

$$\rho_c = v_T / \Omega_c = c\sqrt{Tm} / eB$$

With toroidal field alone the electrons and ions drift in opposite directions. A helical field prevents particle loss by averaging out the drift.

The sources of that helical field defines the different toroidal confinement devices.



$$V_{\nabla B} = \frac{c\mu B \times \nabla B}{eB^2} \qquad V_E = \frac{E \times B}{B^2}$$

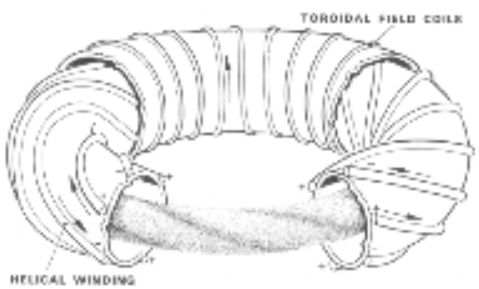
Two Promising Approaches are the Tokamak and Stellerator

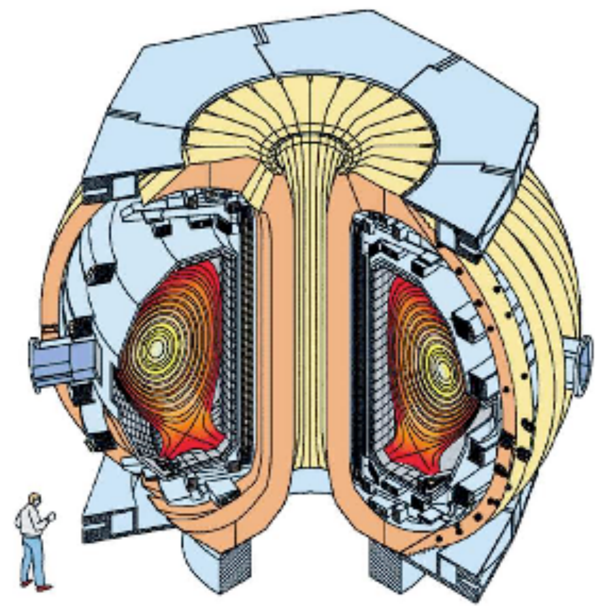
Stellarators have (near) zero toroidal field, and impose the helical twist externally.

Complex coil systems.
Weak/no current driven instabilities.

Tokamaks use a large toroidal current in the plasma to obtain the helical field.

Simple coil systems.
Current driven Instabilities.

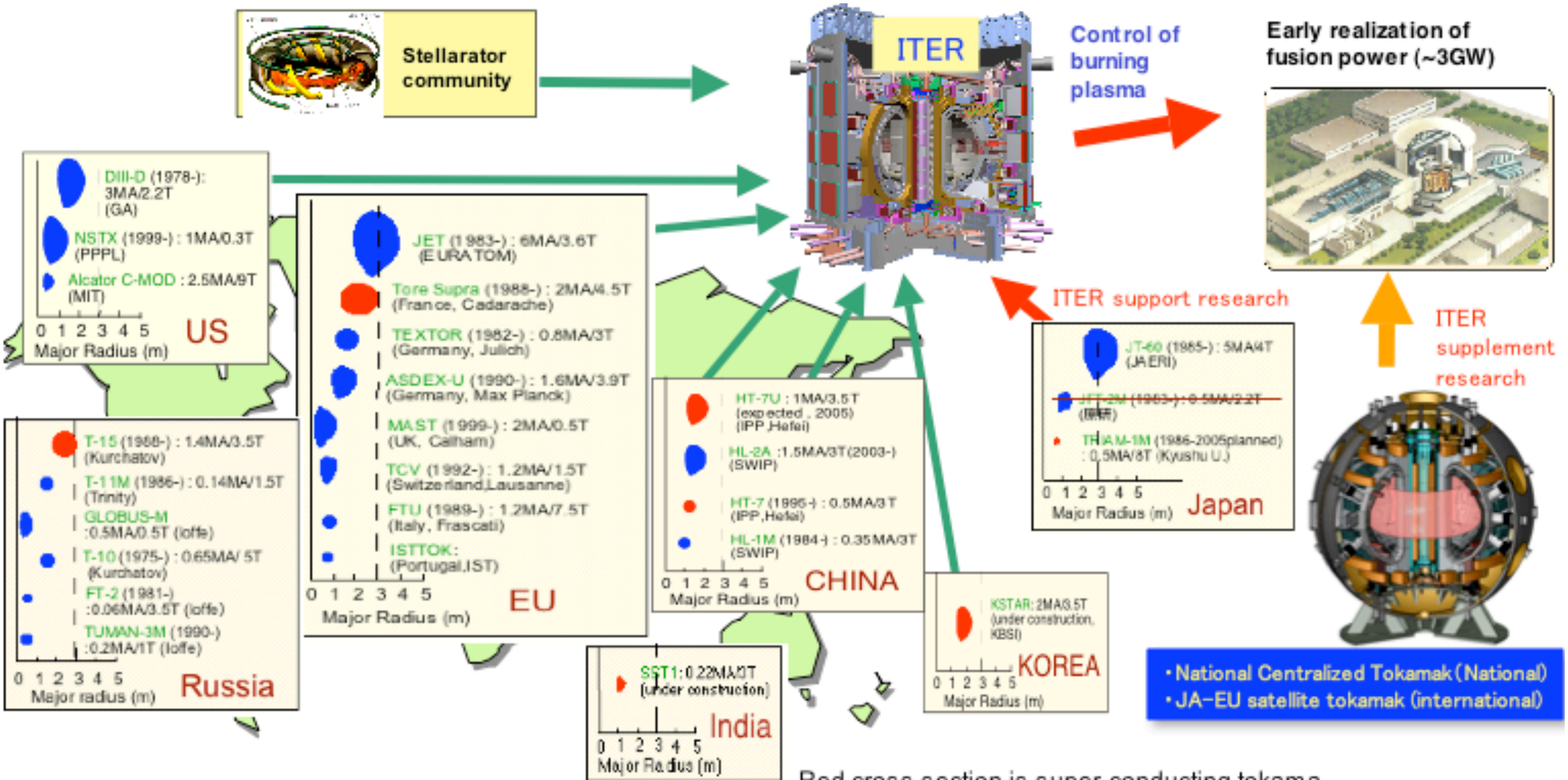




Related approaches include spheromaks, RFPs, FRCs

World Tokamak Research Programs

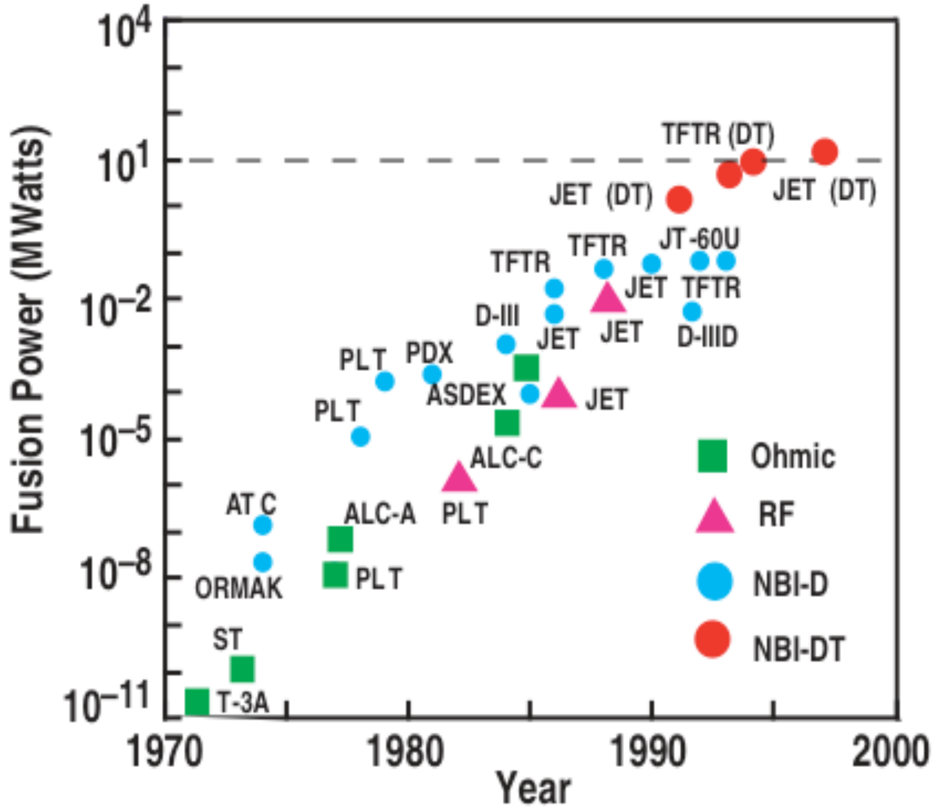
-Significant research programs in several countries
-Seven entities below partnering to focus on ITER project



Red cross section is super-conducting tokama

GENERAL ATOMICS

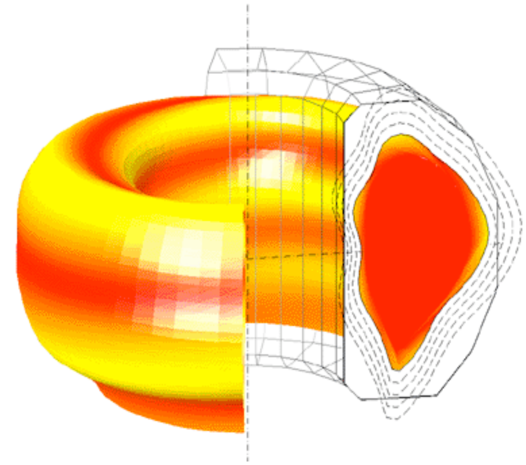
Tokamak Fusion has Made Substantial Progress



- Faster than Moore's Law, approaching Q=1
- ITER designed for ~400MW, Q~5-10

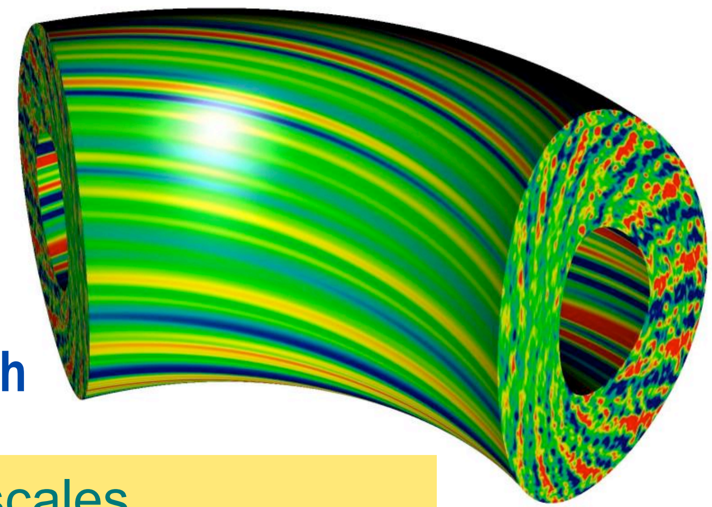
Optimizing Large and Small Scale Physics Key to Fusion Performance

$$\frac{P_{fus}}{P_{loss}} \propto nT\tau_E \propto B^2\beta\tau_E$$



- **Macroscopic Stability**
  - p' and j provide free energy for MHD instabilities
  - Equilibrium spatial scales
  - Low *n* MHD codes

⇒"β limits" - increase with broadness of pressure profile



- **Microscopic Transport**
  - Microinstabilities associated with drift motion
  - Gyrokinetic theory, turbulence simulations, gyroradius scales

⇒"Stiff transport" - roughly fixed gradient scale length

Will focus on physics at large and intermediate scales, magnetohydrodynamcis (MHD)

Outline: Physics Issues for Optimizing Tokamak Fusion Performance

- **Global pressure limits**
  - MHD physics, kink and ballooning modes
  - Resistive Wall Modes
  - Neoclassical Tearing Modes
- **H-Mode and the edge transport barrier**
  - Edge Localized Modes
- **The Advanced Tokamak**
  - Steady state, high performance

Fundamental Description of a Plasma

- **Plasma kinetic equation**

$$\frac{d}{dt} f_\alpha(\mathbf{x},\mathbf{v},t) = \frac{\partial f_\alpha}{\partial t} + \mathbf{v}\cdot\nabla f_\alpha + \frac{q_\alpha}{m_\alpha}\left(\mathbf{E}+\mathbf{v}\times\mathbf{B}\right)\cdot\nabla_{\mathbf{v}} f_\alpha = \sum_\beta C_{\alpha,\beta}(f_\alpha, f_\beta)$$

- **Maxwell's equations** $\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$ $\quad \nabla\cdot\mathbf{E} = \rho_q$

$$\rho_q = \sum_\alpha q_\alpha \int f_\alpha d^3\mathbf{v} \qquad \nabla\times\mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J} \qquad \mathbf{J} = \sum_\alpha q_\alpha \int f_\alpha \mathbf{v} d^3\mathbf{v}$$

- **Contains all information about plasma dynamics (classical, non-relativistic)**
- **Impossible to solve analytically in any but special cases**
- **Six dimensions and wide range of spatiotemporal scales makes numerical solution impractical in all but simple cases**
- **Need to simplify for practical solution**
  - Gyrokinetics: averages over fast cyclotron timescale (5D)
  - Fluid ("MHD"): take moments of distribution functions (3D)
    - Useful for large scale physics, wide range of timescales

Deriving MHD Equations

- **Define moments of distribution function**

$$M_n(x,t) = \int_{-\infty}^{\infty} f(x,v,t)\,v^n\,dv$$

- **Knowledge of *N* moments allows (in principle) reconstruction of *f* at *N* points in velocity space**
- ***N* moments of plasma kinetic equation => *N* fluid equations satisfied by M_{N+1}**
  - Each additional moment equation yields more information about velocity distribution
- **Use low order truncation and closures**

Deriving MHD Equations

Left with series of moment equations for density, fluid velocity and temperature

$$\frac{\partial n}{\partial t} + \nabla \cdot nV = 0$$

$$Mn\frac{d\mathbf{V}}{dt} = -\nabla p + \mathbf{J} \times \mathbf{B} - \nabla \cdot \Pi$$

Viscous Stress

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J}$$

Resistivity

$$n\frac{\partial T}{\partial t} + n\mathbf{V} \cdot \nabla T + (\Gamma - 1)nT\nabla \cdot \mathbf{V} = -(\Gamma - 1)\nabla \cdot \mathbf{q} + (\Gamma - 1)Q$$

$$\mathbf{q} = -(\kappa_{\parallel} - \kappa_{\perp})\nabla_{\parallel} T - \kappa_{\perp} \nabla T$$

Thermal Anisotropy

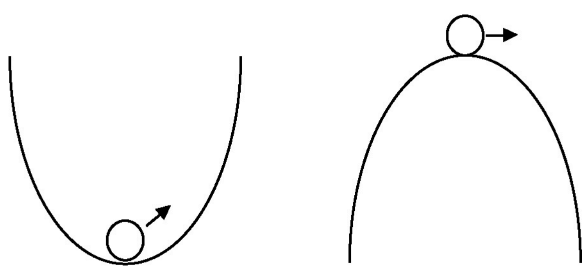
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

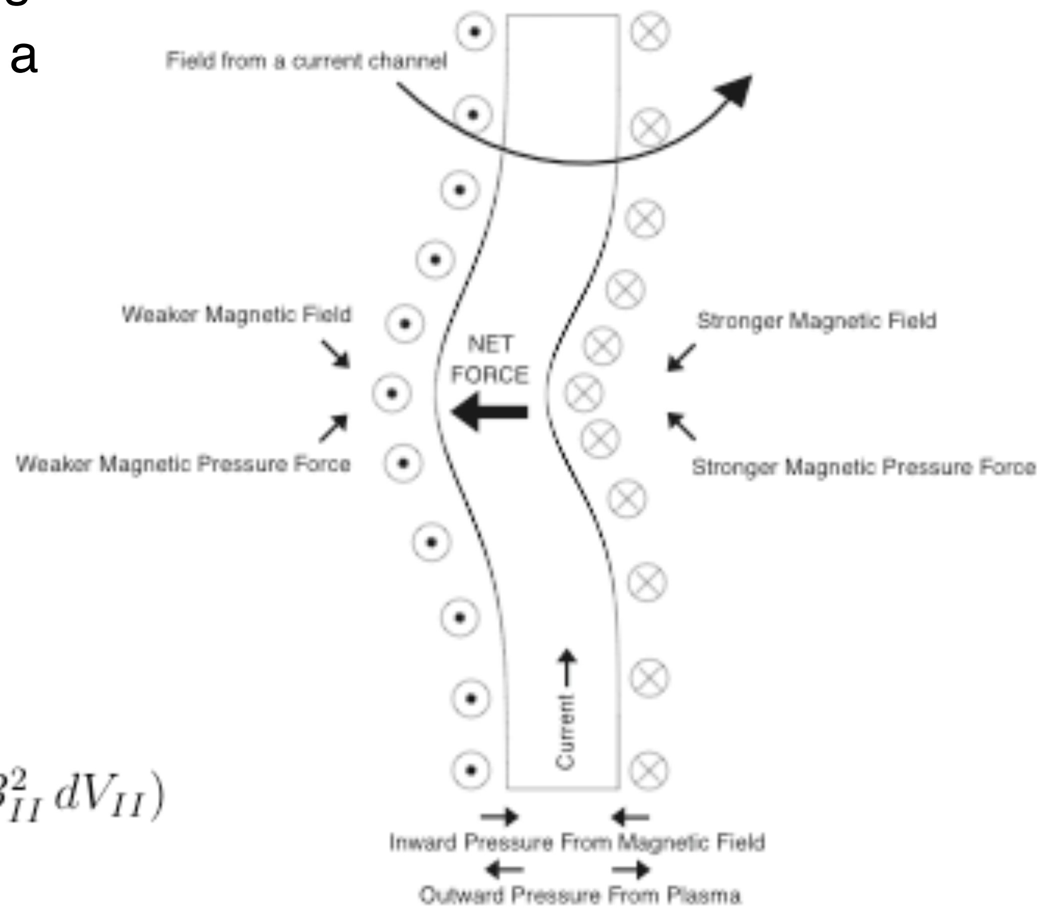
$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

Ideal MHD omits diffusive terms, useful for studying fast, large scale instabilities

MHD Instabilities

Perturbative δW method finds linear change in energy with a small perturbation; reduction is unstable.

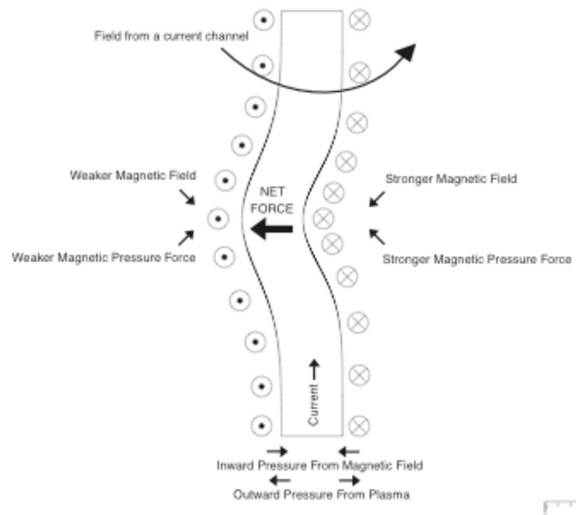


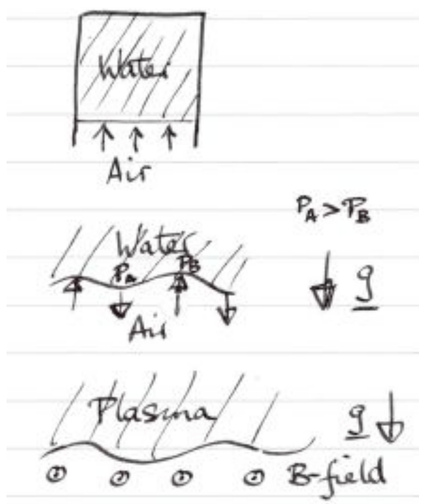


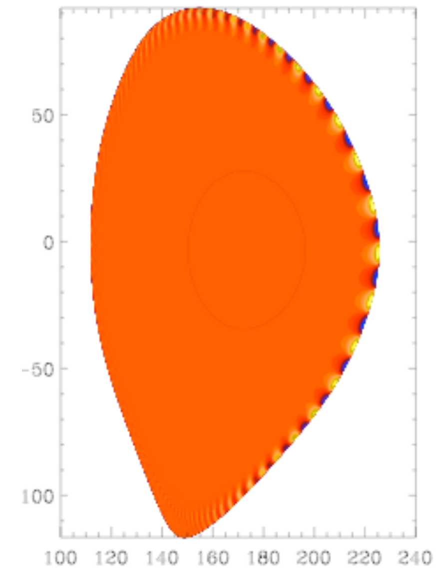
$$\triangle W = \frac{1}{2\mu_o}\left(\int_{V_I} B_I^2\, dV_I - \int_{V_{II}} B_{II}^2\, dV_{II}\right)$$

MHD Instabilities: Kink and Ballooning Modes

- **Current and Pressure Gradient provide large sources of free energy**
- **Kink modes are current driven**
- **Ballooning modes are pressure driven**
  - Variant of interchange mode, bad curvature
- **In practice, external kinks with both current and pressure drive often limiting**
  - Efficient numerical tools developed to calculate beta limits







GENERAL ATOMICS

Good Agreement Between Predicted and Observed MHD Beta Limits

- **Numerical calculations suggest systematic β_N limit**
  - Good agreement with multiple observations
- **Limit increases with strong shaping and optimized profiles**
- **Conducting wall near plasma can stabilize modes, increase β_N limit**
  - Mode that results is slow growing Resistive Wall Mode

Theory calculations (1982–1984), Troyon & Sykes

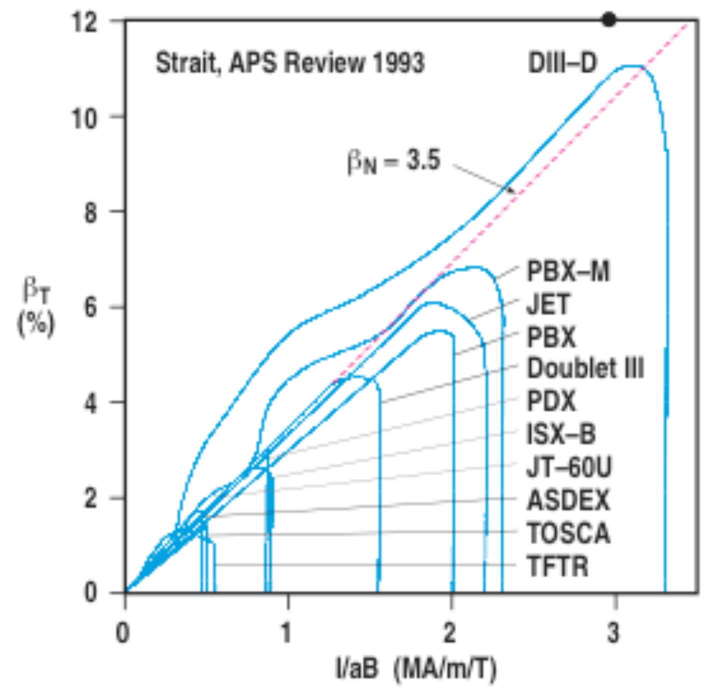
$\beta_T\,(\%) \le 2.8 \dfrac{I\,(MA)}{a(m)\,B_T\,(T)}$, Define $\beta_N = \beta_T/(I/aB)$

2.8 = Troyon-kink
4.4 = Sykes-balloon

$$\beta_p\,\beta_T = 25\left(\frac{1+\kappa^2}{2}\right)\left(\frac{\beta_N}{100}\right)^2$$

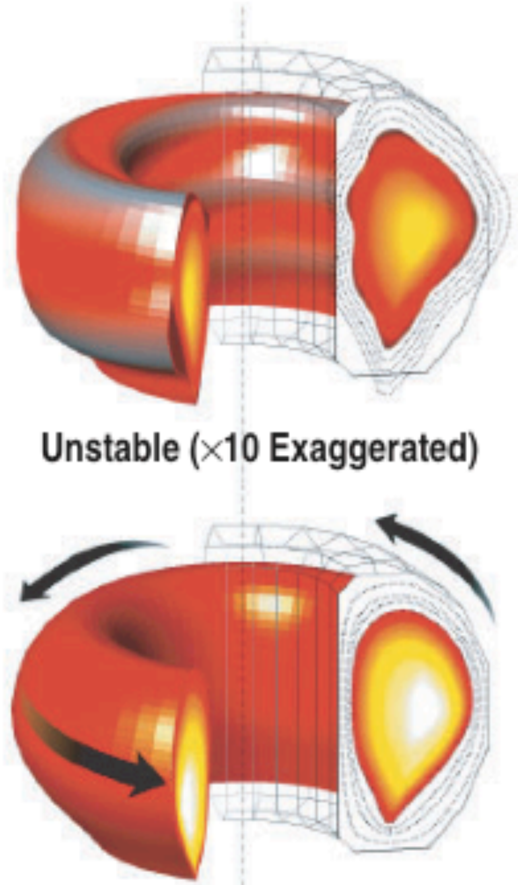
Fusion power $\beta_T^2\,B^4$

Bootstrap fraction $c\varepsilon^{1/2}\,\beta_p$

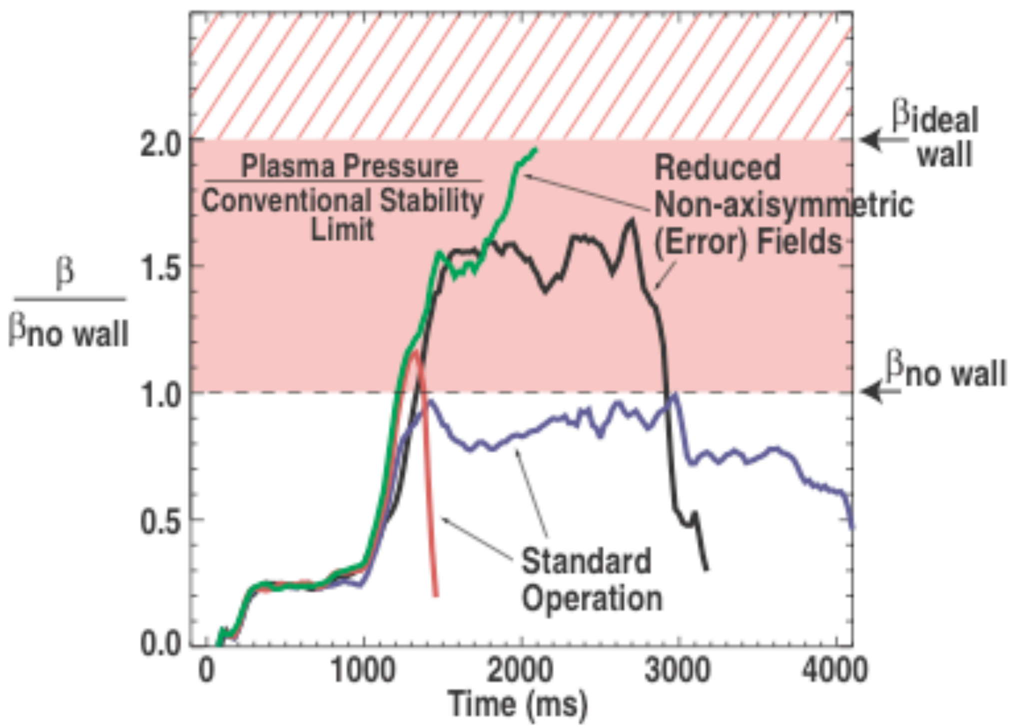


GENERAL ATOMICS

Rapid Rotation Stabilizes RWM, allows High β Operation



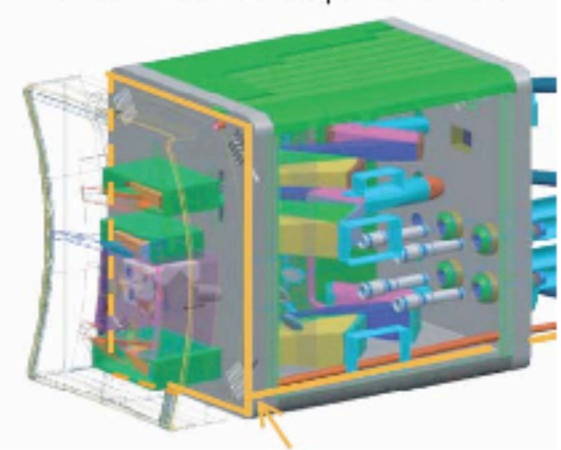
- External coils reduce error fields (reduce magnetic drag) and permit neutral beam to induce rapid rotation



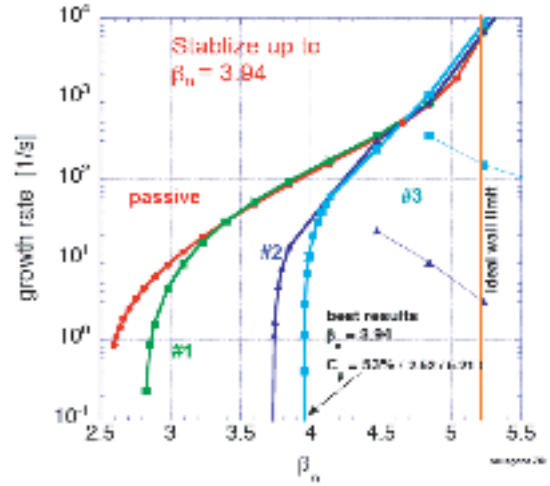
Slower Expected Rotation on ITER Motivates RWM Feedback Stabilization Research

- ITER base design includes control coils
  - Error field correction: far behind vessel, blanket
  - Feedback controlled $\beta_N \approx 2.5 \Rightarrow 2.9\text{-}3.3$
- USA use in-vessel coils behind shield
  - VALEN: plasma surface current model of RWM + 3D structure circuit model
  - Blanket $\Rightarrow$ n=1 ideal-wall limit $\beta_N \approx 4.5\text{-}5$
  - Feedback controlled $\beta_N \approx 2.5 \Rightarrow 4$

RWM Coil Concept for ITER



Coil behind shield module

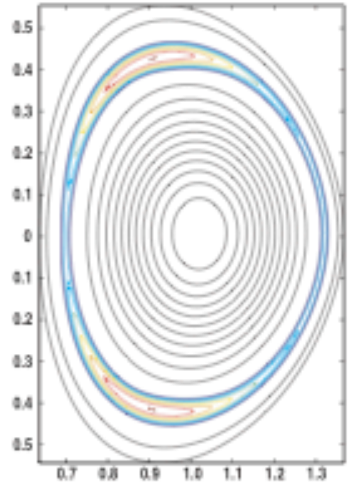


7 RWM Coils mounted behind the blanket in every other port except NBI ports. (assumes 9 ms time constant for each blanket shield module)

Preliminary result: Successful RWM feedback stabilization on DIII-D last week (turned neutral beam around to allow low rotation)

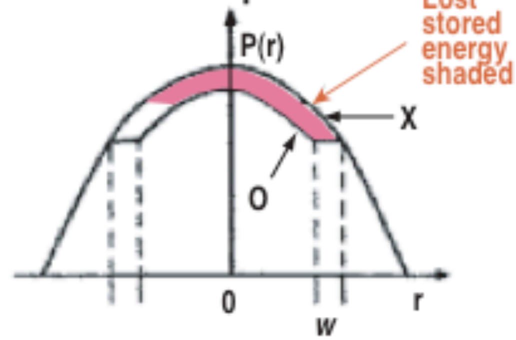
Magnetic Reconnection leads to Tearing Modes which can Limit β below Ideal values

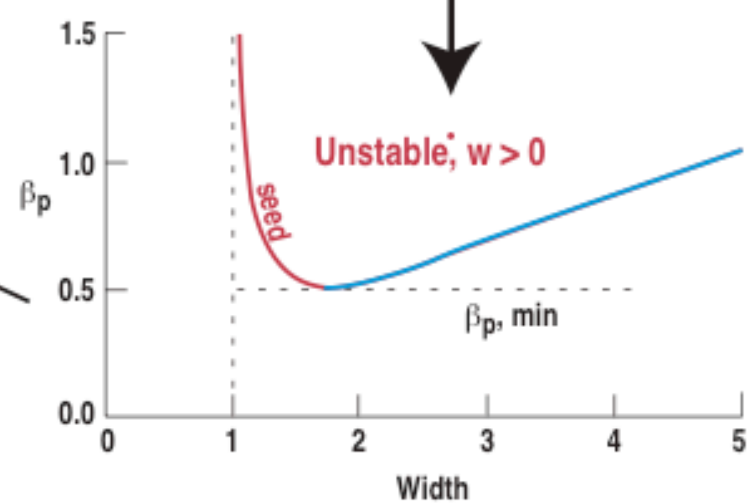
Island Formation at Rational Surface



PEST–III

Helically Perturbed Pressure and Bootstrap Current

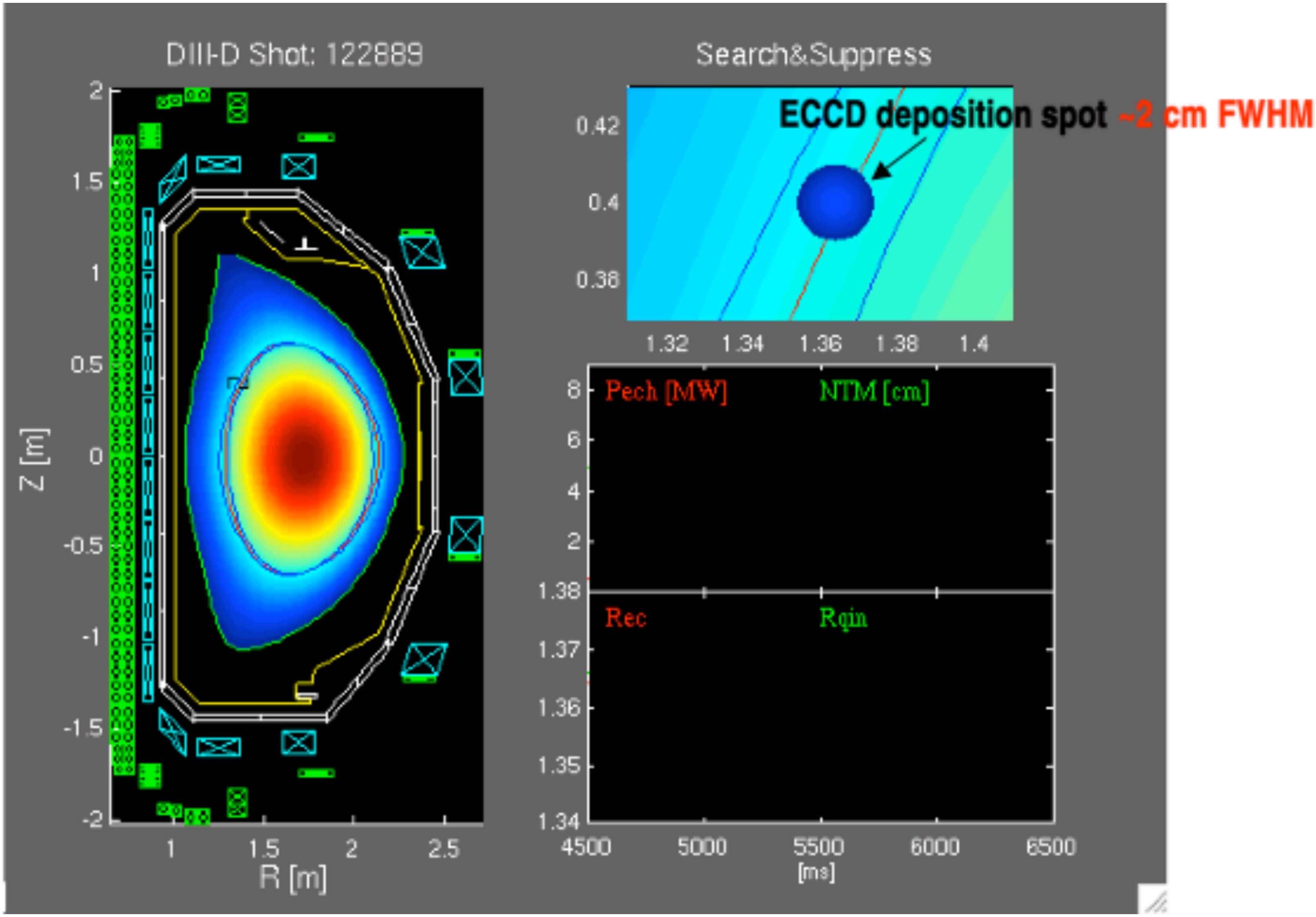




Any Significant Seed Island Leads to Limit on Achievable β

- Choices if High β Desired:
  - Avoidance
  - Stabilization

NTMs Can Be Stabilized Via Carefully Aimed Driven Current



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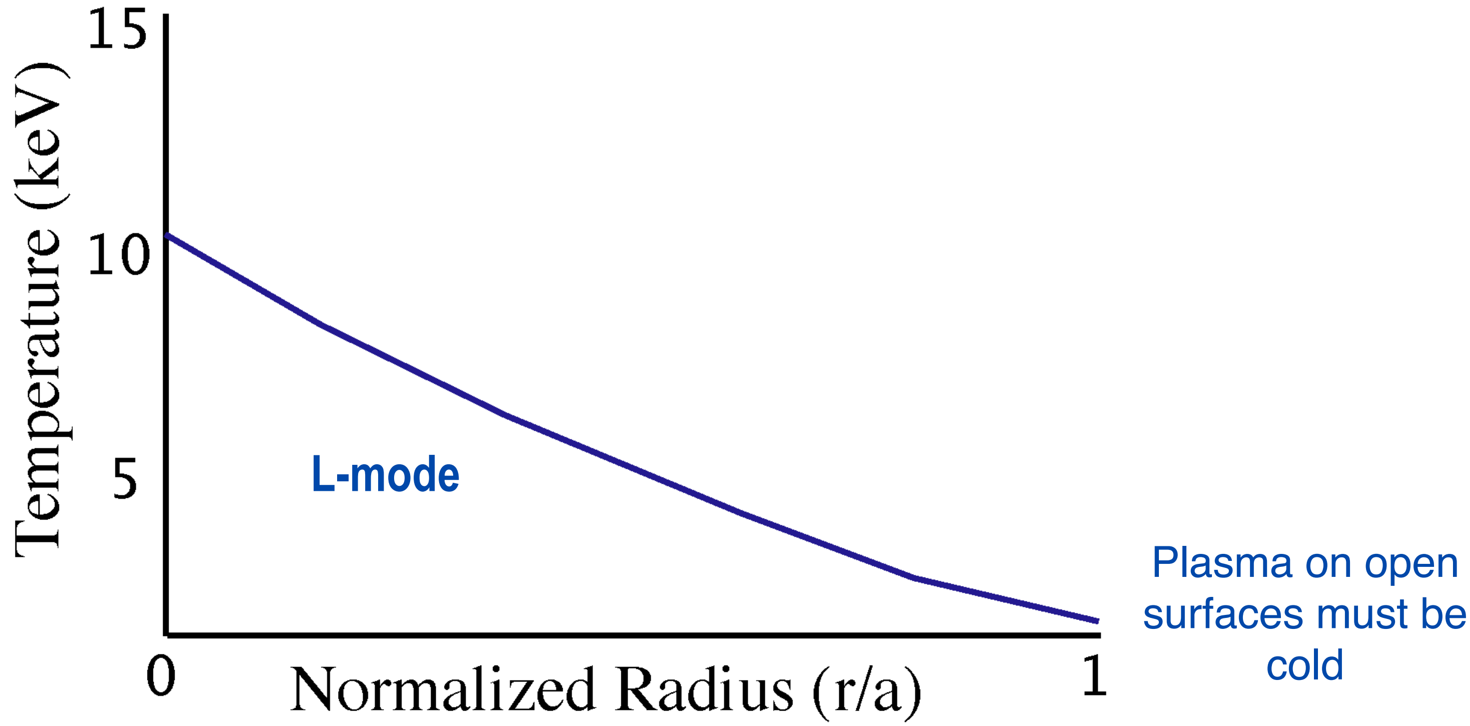
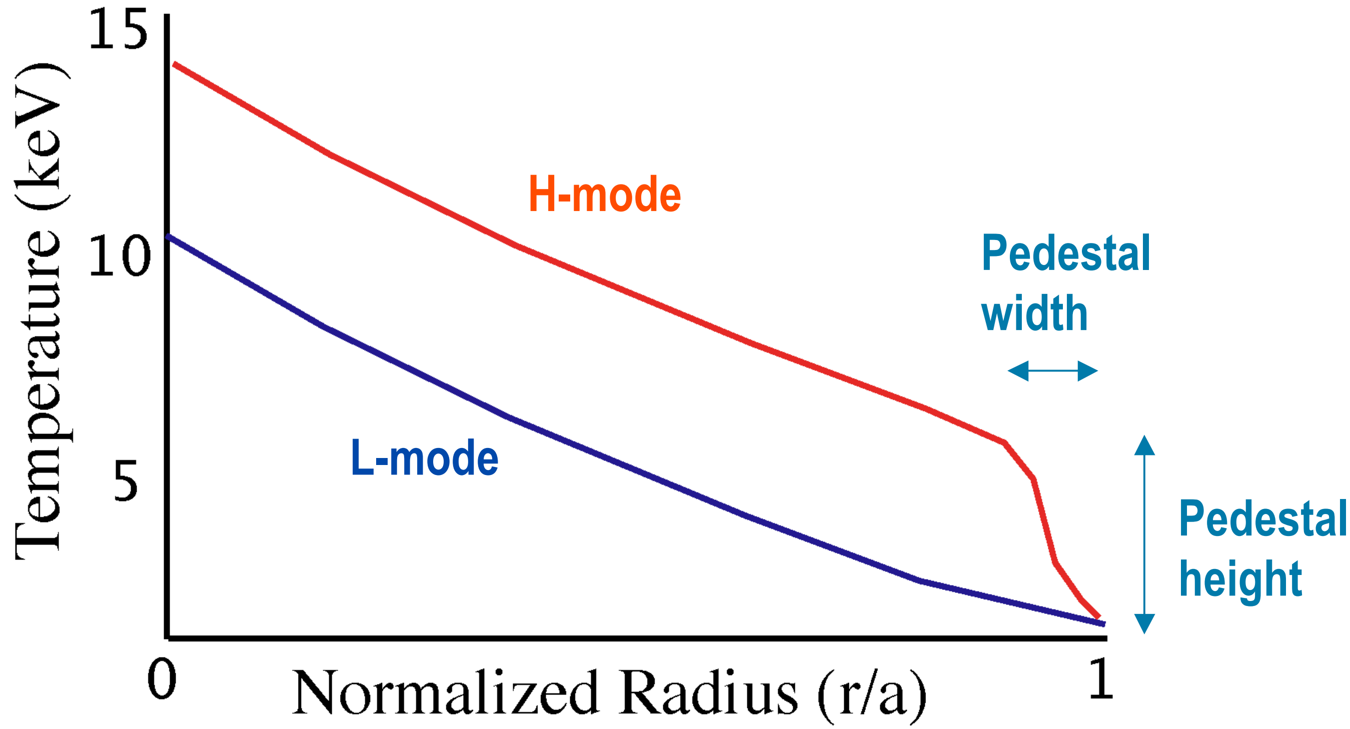
High Performance via the Edge Transport Barrier



- **Stiff transport implies approximately fixed gradients in core**
  - L-mode: Better confinement requires bigger machine ($$$)

High Performance via the Edge Transport Barrier

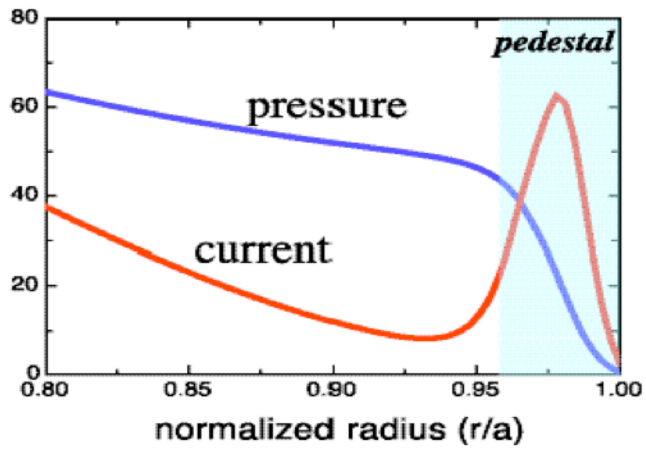


- **Stiff transport implies approximately fixed gradients in core**
  - L-mode: Better confinement requires bigger machine ($$$)
- **H-mode pedestal lifts whole profile (dramatic for fixed scale length)**
  - Profile broadening raises MHD beta limit
  - “Height” of the pedestal key to performance

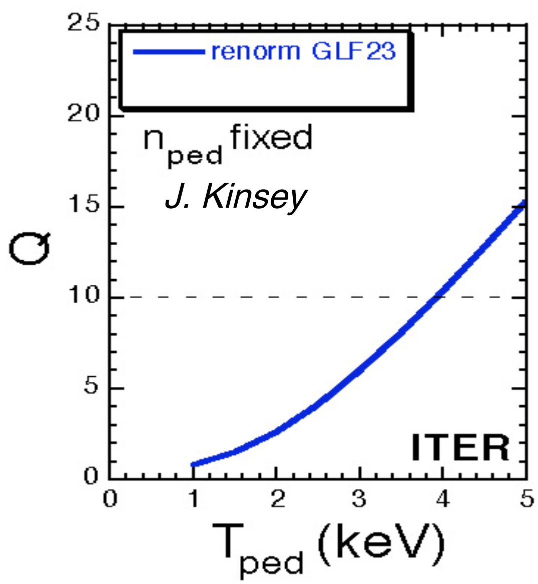
H-mode is reference operating mode for ITER and projected fusion reactors

Physics of the Pedestal and ELMs

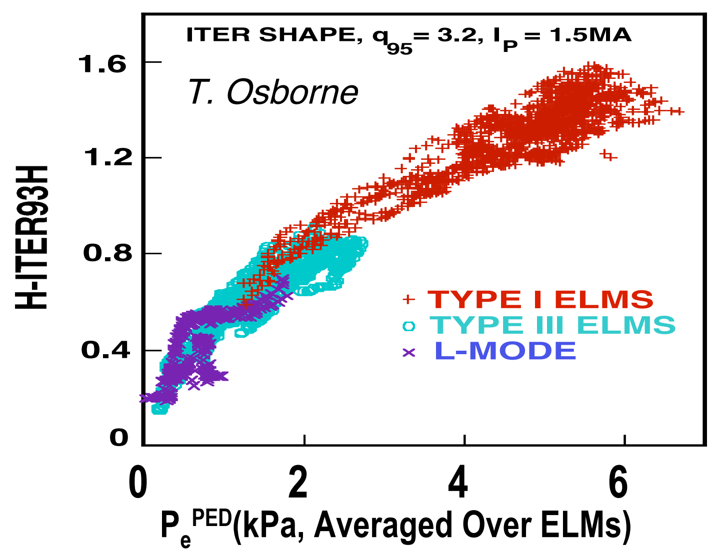
- **ELMs and the edge pedestal are key fusion plasma issues**
  - "Pedestal Height" strongly impacts core confinement and therefore fusion performance (Q)
  - ELM heat pulses impact plasma facing materials
  - *Both very high priority for ITER*



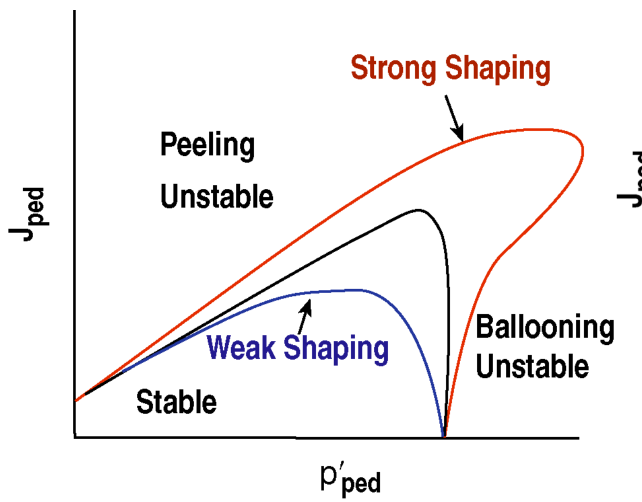
Predicted Impact of Pedestal Height

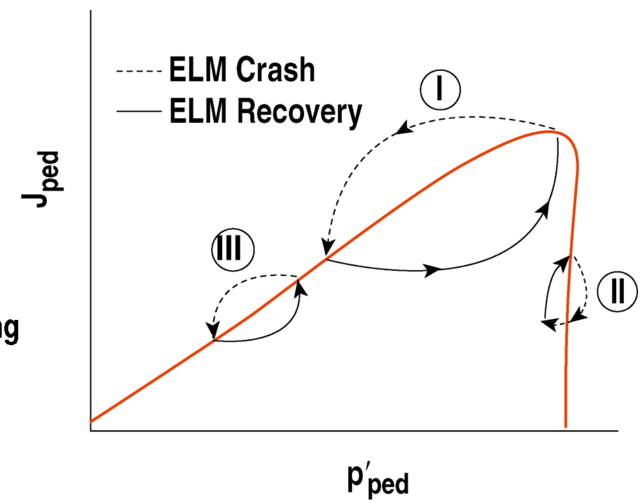


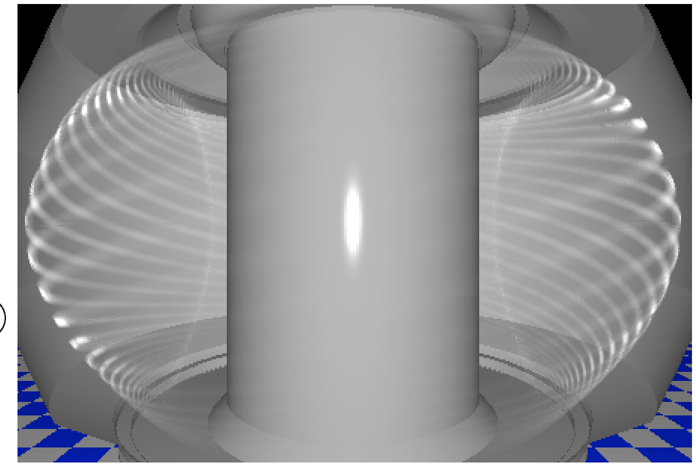
Observed Impact of Pedestal Height



The Peeling-Ballooning Model





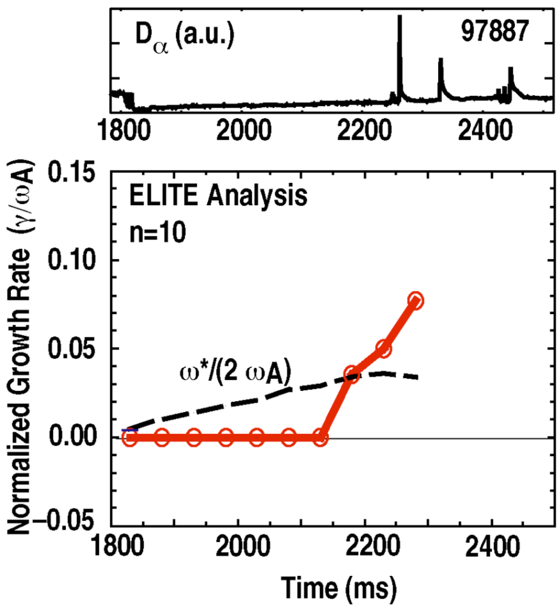


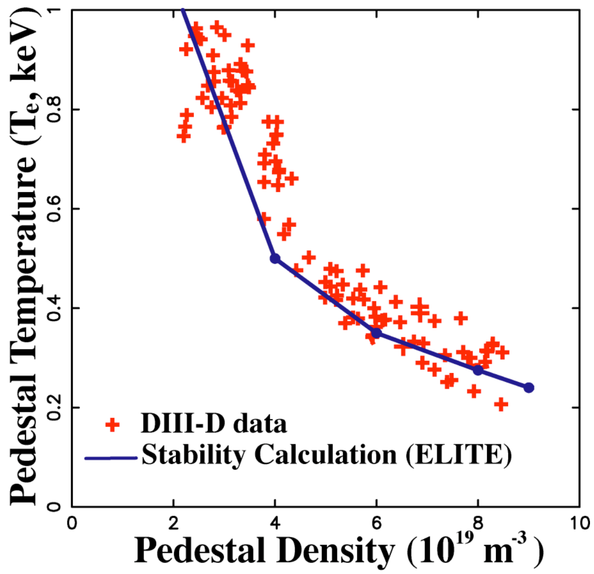
n=18 mode structure

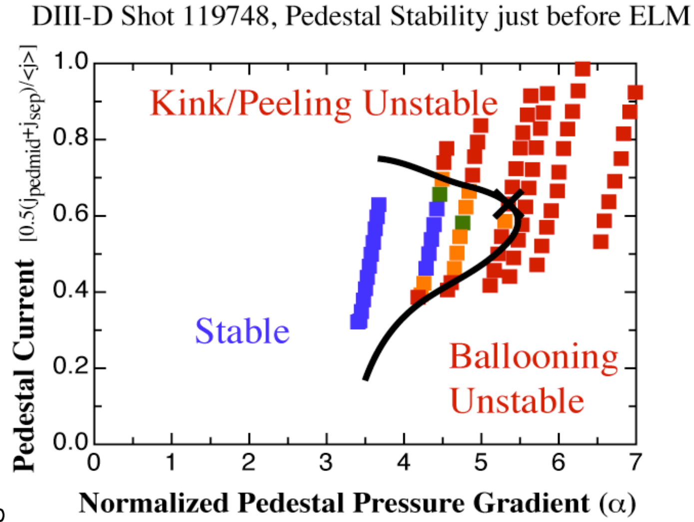
- **ELMs caused by intermediate wavelength (n~3-30) MHD instabilities**
  - Driven by pressure gradient and current in the edge transport barrier region
  - Complex dependencies on ν_*, shape etc. due to bootstrap current and “2nd stability”

GENERAL ATOMICS

The Peeling-Ballooning Model: Validation

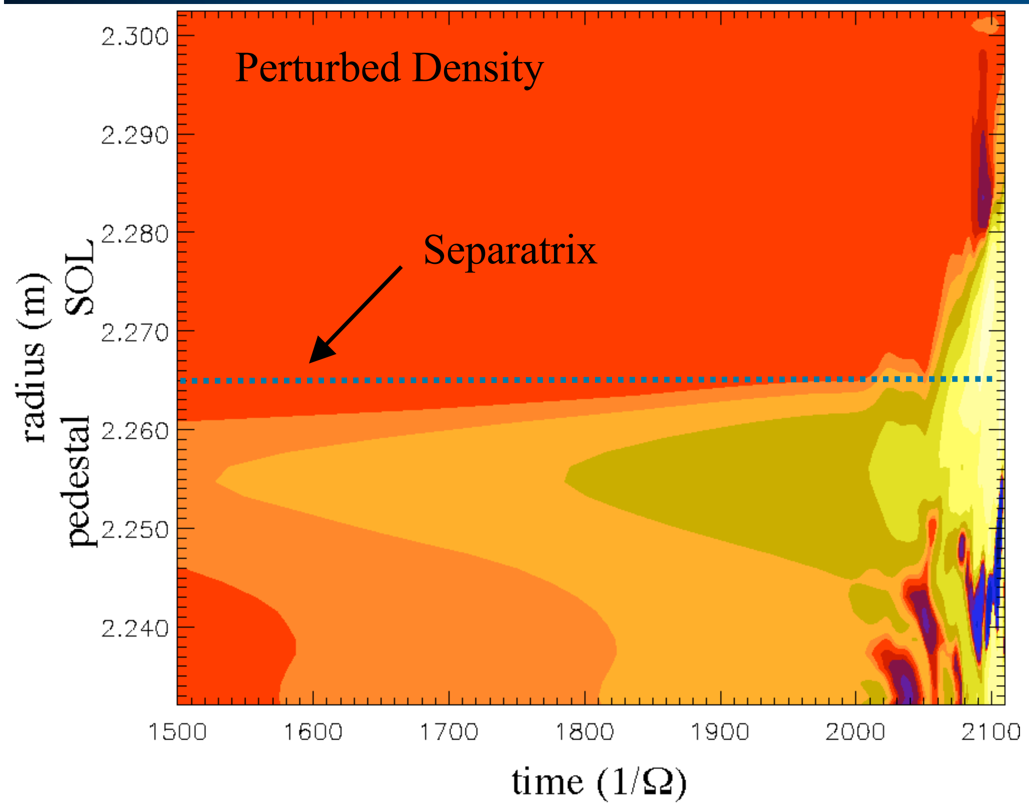


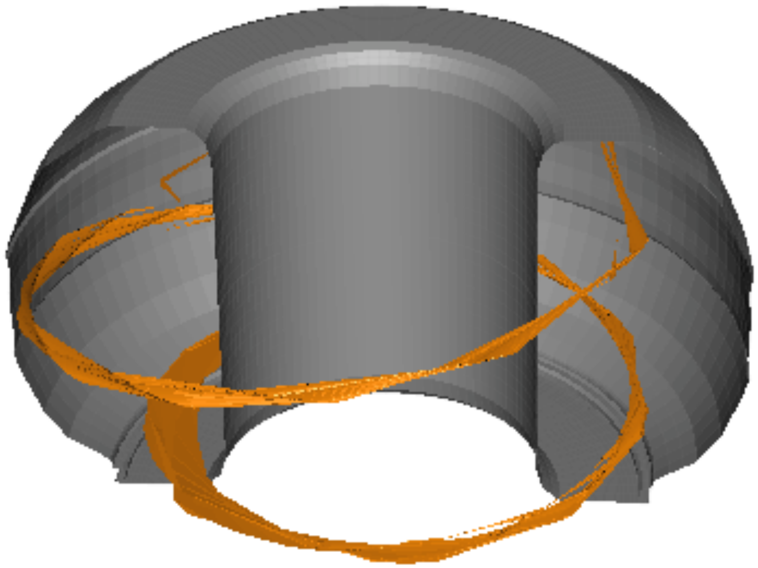




- **Successful comparisons to expt both directly and in database studies**
- **MHD physics, taking into account two fluid effects, does a remarkably good job of accounting for ELM onset and observed pedestal constraints**
  - Allows performance projections for ITER, though barrier width remains a significant uncertainty

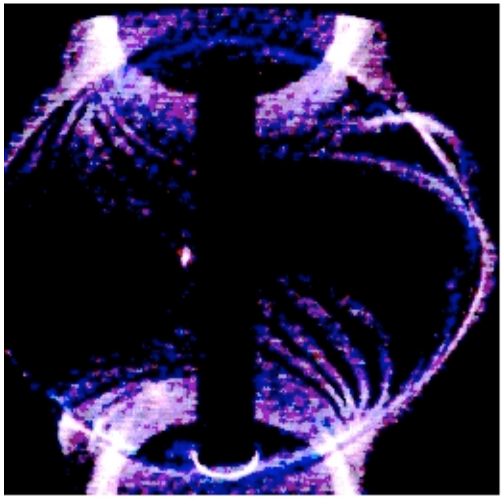
Nonlinear Simulations of ELMs Exploring Evolution and Heat Deposition

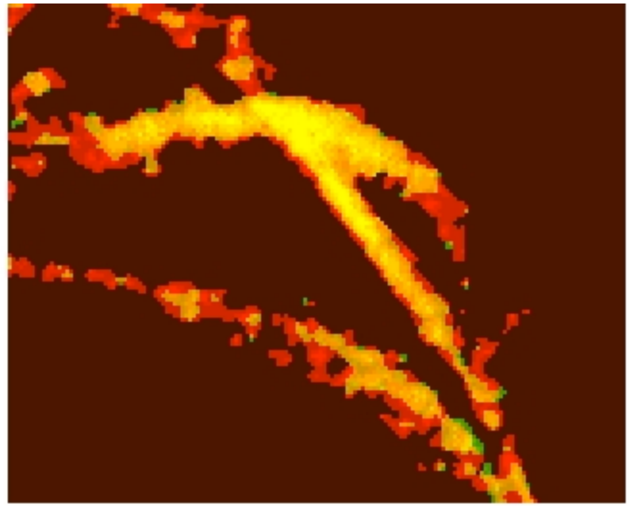




- **Initial linear growth phase (n~20, γ/ω_A~0.15), then fast radial burst begins at t~2000, can see positive density (light) moving into SOL and negative perturbed density near pedestal top**
- **Radial burst has filamentary structure, extended along B**

Fast ELM Observations

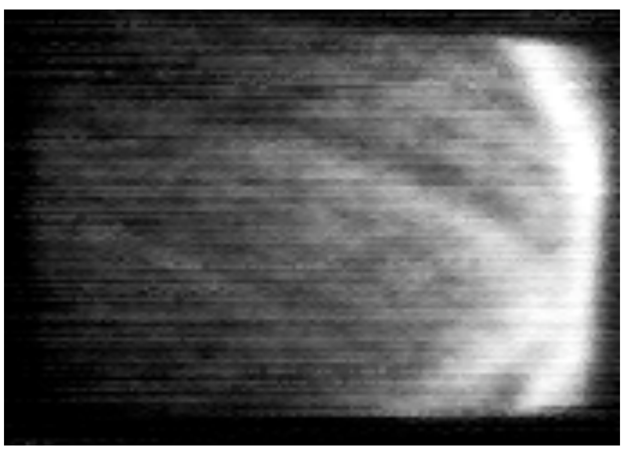


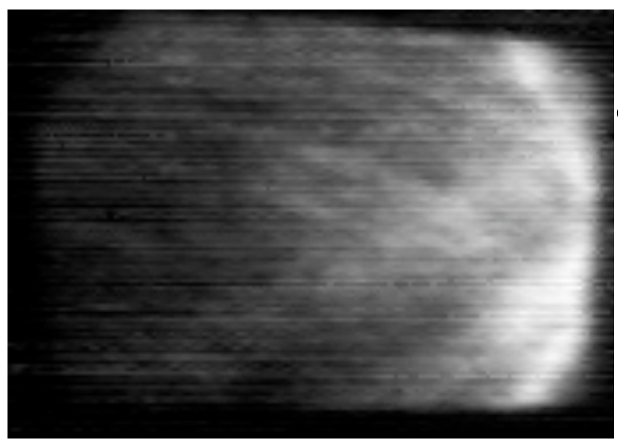


A. Kirk, MAST, PRL 92 (2004) 245002-1

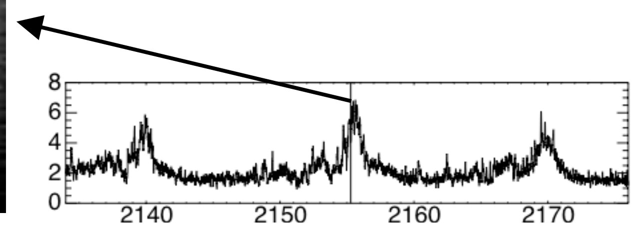
- n=10 structure on outboard side
- Filaments moving radially outward

M. Fenstermacher, DIII-D, IAEA 2004

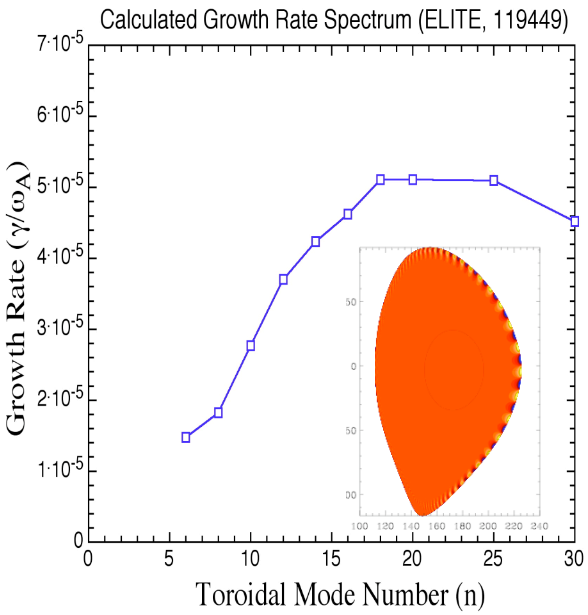




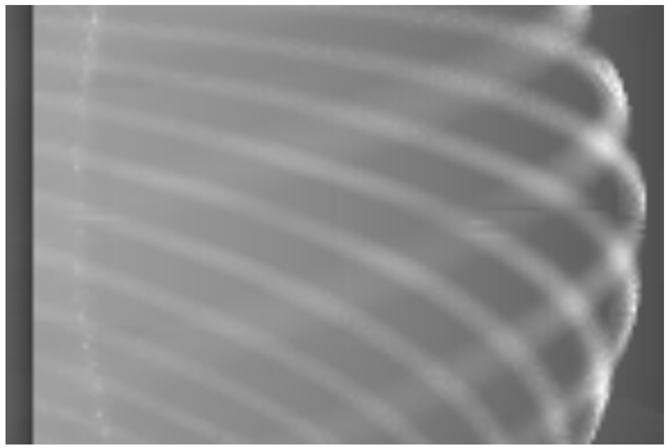
- CIII images from fast camera on DIII-D
- n~18 inferred from filament spacing



DIII-D ELM Images Compared to Simulations

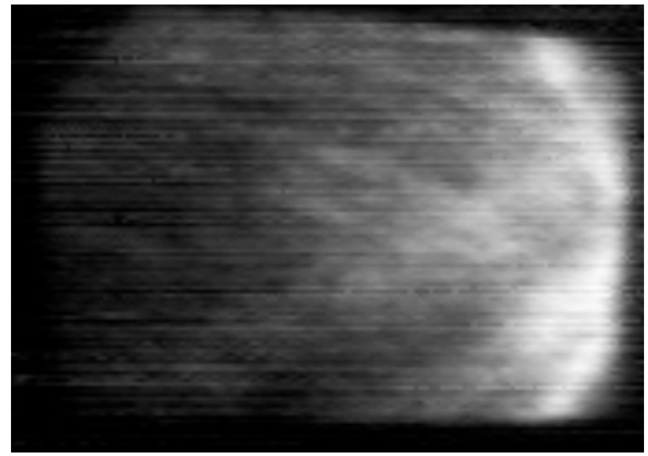


ELITE, n=18

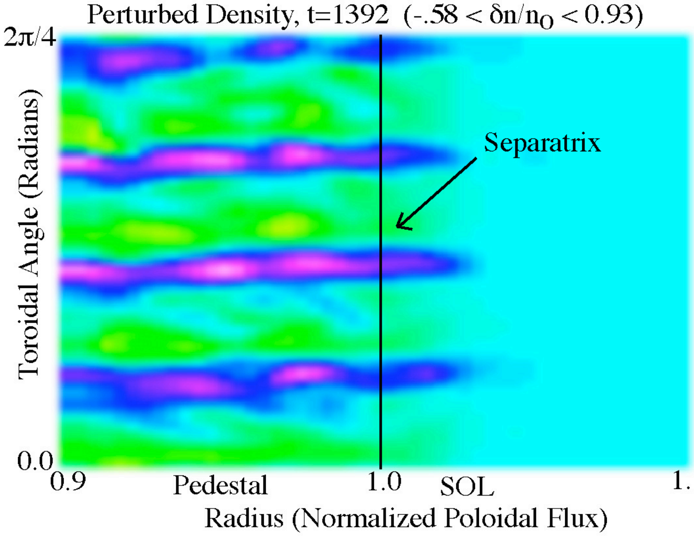


Fast CIII Image, DIII-D 119449

M. Fenstermacher, DIII-D/LLNL



BOUT, nonlinear burst phase

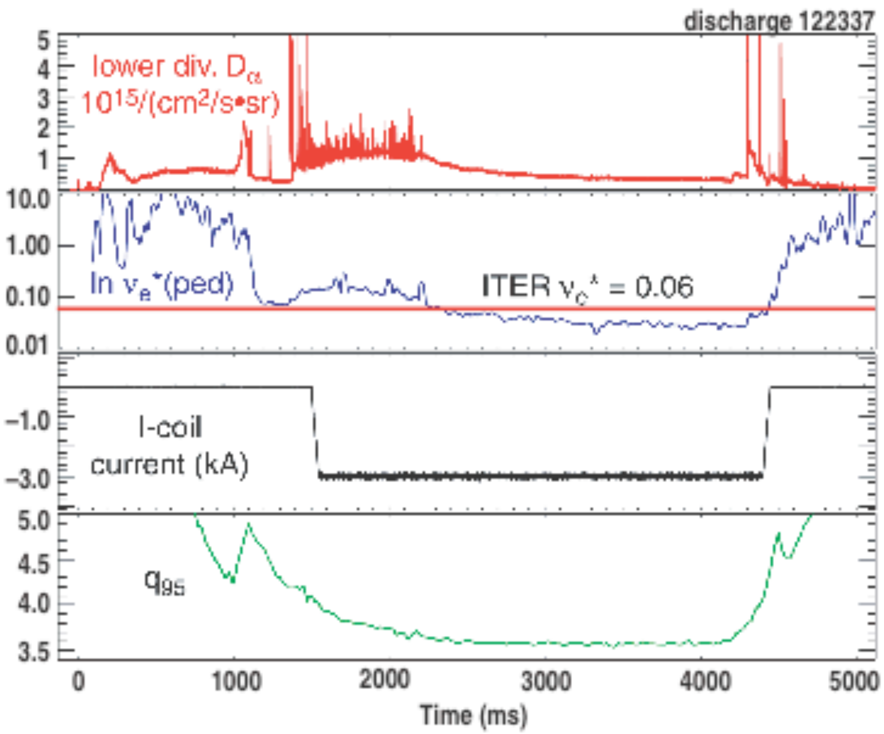


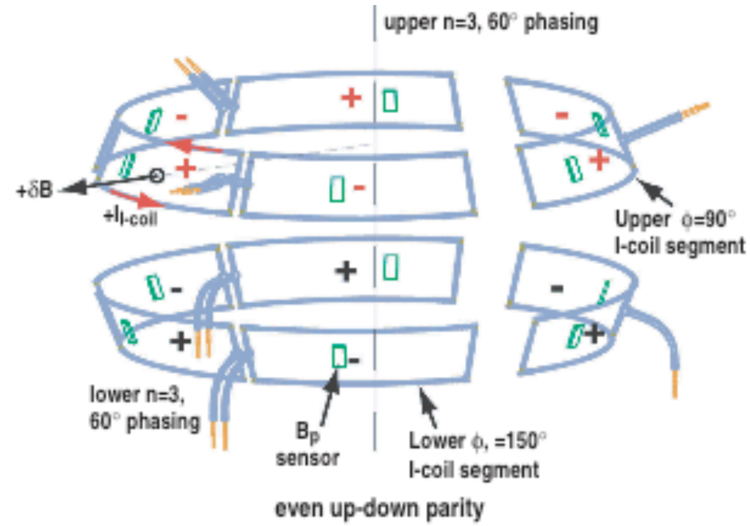
- **ELITE linear P-B calculations show peak 15<n<25; mode in this range predicted to be first to go unstable**
- **Calculated n=18 structure qualitatively similar to observations**
- **Nonlinear simulations show symmetric stucture in early phase, extended uneven filaments later**

GENERAL ATOMICS

ELMs Successfully Suppressed Using Non-Axisymmetric Magnetic Perturbation

- n=3 magnetic field from I-coil perturbs plasma edge





- No degradation in core confinement or increase in core radiation

Pedestal pressure held below ELM stability limit
Transport physics not fully understood: Not simple stochastic transport

Outline: Physics Issues for Optimizing Tokamak Fusion Performance

- **Global pressure limits**
  - MHD physics, kink and ballooning modes
  - Resistive Wall Modes
  - Neoclassical Tearing Modes
- **H-Mode and the edge transport barrier**
  - Edge Localized Modes
- **The Advanced Tokamak**
  - Steady state, high performance

The Advanced Tokamak Concept Allows High Performance, Steady State Operation

- **Conventional Tokamak**
  - Current is inductively driven (pulsed operation)
  - Low β (β_N~2), L-Mode confinement (no pedestal)
  - Large machine required for power plant ($$)
- **Advanced Tokamak (AT)**
  - Current is non-inductively driven (steady state)
    - Substantial fraction is self-driven bootstrap current
  - High β (β_N>~4), H-Mode or better confinement (high pedestal)
  - Compact, high duty cycle power plant

High β_N is Key to Success of Advanced Tokamak

- **High β is essential for high fusion power in a compact machine (P_{fus}~$V\beta^2B^4$)**
- **High β (β_p~$\beta B^2/I^2$) also essential for getting a high fraction of self-driven bootstrap current (f_{BS}~$\varepsilon\beta_p$)**
  - High bootstrap fraction needed for cost-effective steady state operation
- **Similar physics which allows high global β_N also allows high pedestal, which leads to good confinement**
- **Optimizing normalized β_N is essential, both for high fusion performance and steady state: gains are multiplicative**

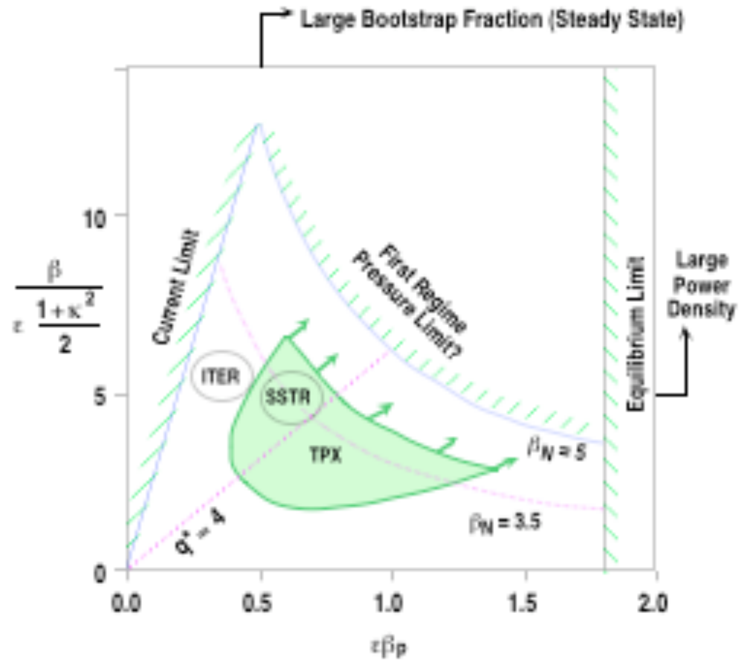
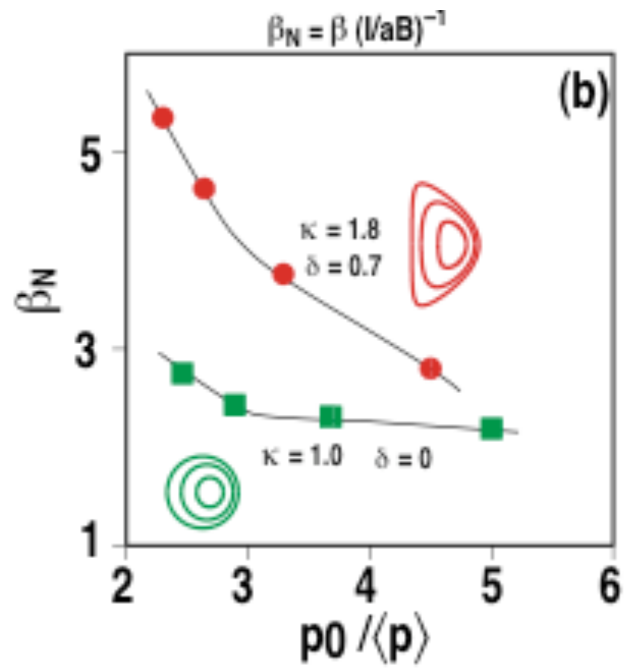


Fig. 1. A compact steady-state tokamak requires operation at high β_N. Advanced tokamak operation is toward the upper right hand corner, high β_N.

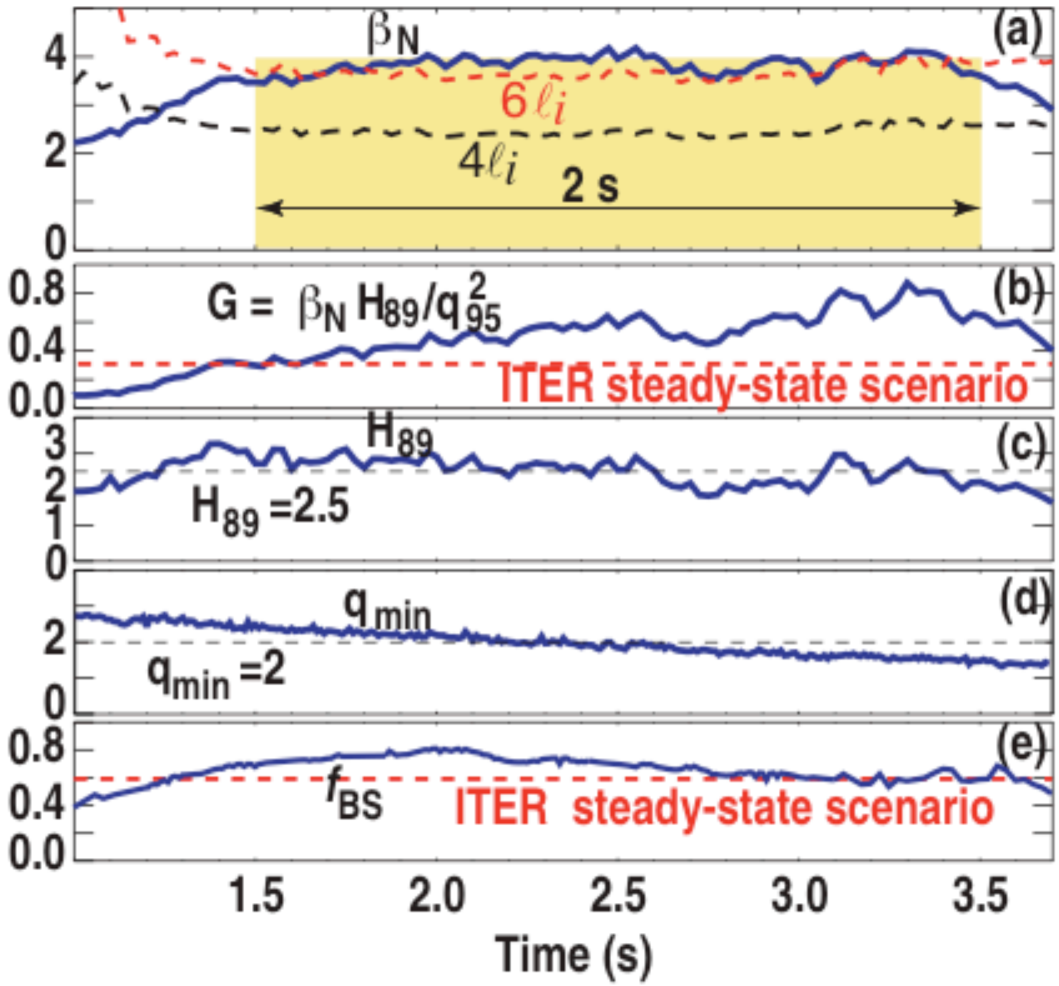
Multiple Tools and Techniques Applied to Optimize AT Performance

- **Strong shaping allows high MHD limits on global β_N**
  - Current and pressure profile optimization using neutral beams, ECCD, RF
- **RWM stabilized with rotation or active feedback**
- **NTM avoided via profile optimization or stabilized with ECCD**
- **Pedestal height optimized with shaping, ELMs mitigated with RMP or other techniques**



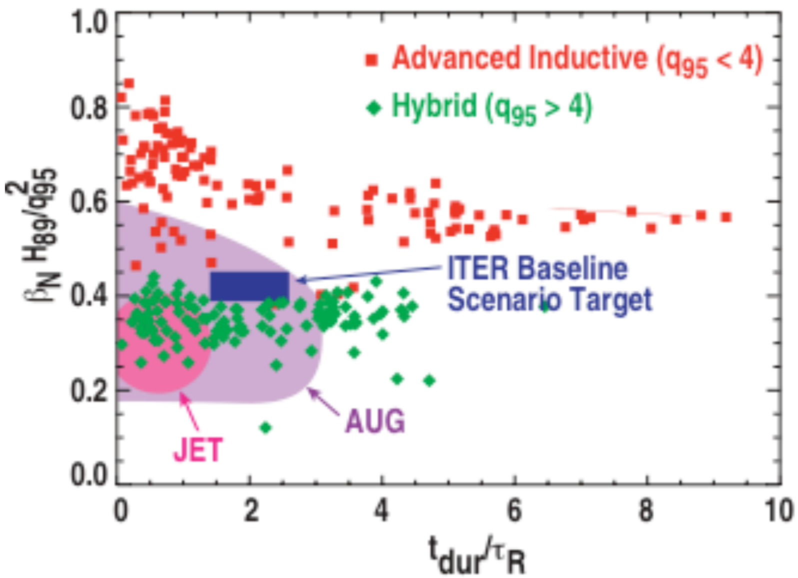
AT leads to sustained high performance on DIII-D and good projections to ITER and fusion reactors

- $\beta_N \sim 4$, $\beta_T \sim 4\text{-}7\%$
- $H_{89} \geq 2.5$
- $f_{BS} \geq 60\%$, $f_{NI} \geq 80\%$
- **C-coil and I-coil used for simultaneous feedback control of error fields and RWM**
- **New tools in FY06–07 will help advance the understanding of RWM control**
  - Balanced injection for ITER-relevant rotation
  - Additional fast amplifiers for larger control currents with low latency

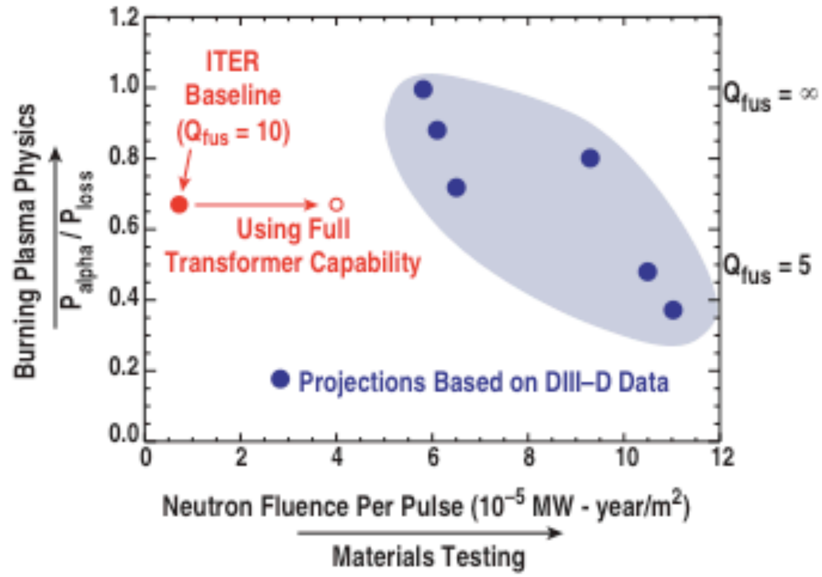


AT Regimes Project to Enhanced Capabilities for ITER and Compact Power Plant Designs

- Performance at or above ITER baseline maintained in stationary conditions



- Projections of DIII-D data suggest expanded research opportunites in ITER



- **ARIES AT reactor study projects 5c/kWh**
  - Many materials engineering and physics issues to be resolved

Summary

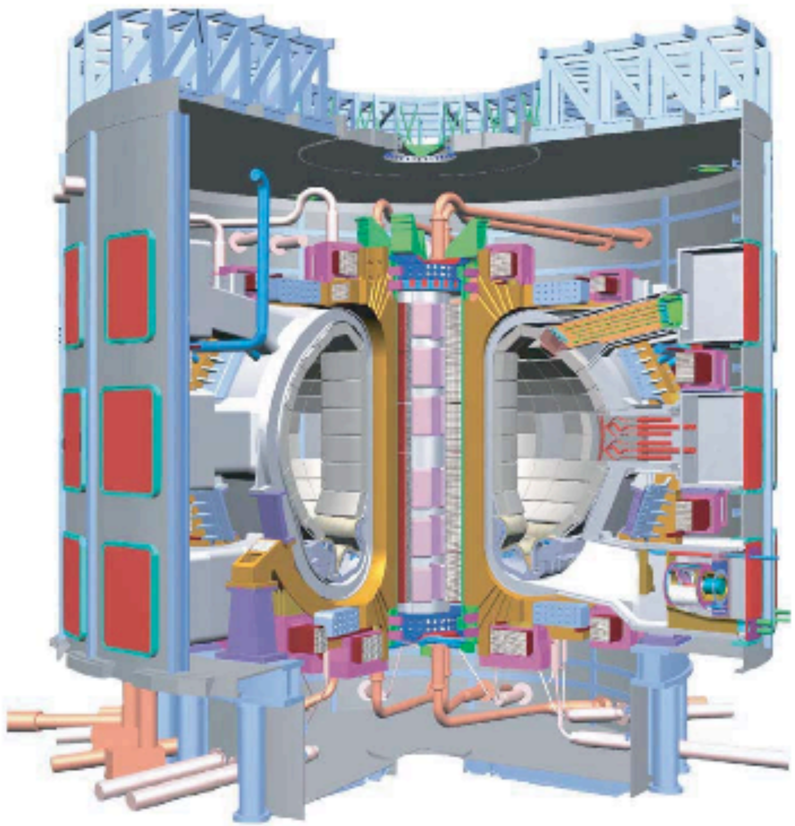
- **MHD physics allows understanding and control of instabilities that govern tokamak performance**
  - Kinks, ballooning modes, RWMs, NTMs, ELMs
- **Optimizing against these constraints using shaping and profile control -> high performance**
- **Doing so in steady state capable scenarios with high bootstrap current -> Advanced Tokamak**
  - High projected performance in ITER. Compact, cost - effective reactor designs possible
  - Many physics and engineering issues remain to be addressed

Sample of Key Open Issues

- **Physics (tokamak)**
  - Full optimization of global beta limits (extreme shapes)
  - Optimum RWM feedback control algorithm
  - NTM physics at small island size
  - Pedestal width and ELM suppression physics
  - Optimize integrated long pulse AT operation
    - ITER required to do so at reactor-like parameters
- **Materials/Engineering (largely generic)**
  - High heat flux (~10MW/m^2), high neutron flux capable materials
    - Retain strength despite neutron activation
    - Minimize tritium retention and production of activated wastes
  - Develop efficient breeding blanket technology

ITER is going forward: Will address physics and materials issues in reactor scale device

- Cost sharing settled 2003
- ITER site decision (France) made June 28,2005
- Negotiation of the final agreement completed
  - "Initialing" May 2006
  - Ratification Fall 2006
- Kaname Ikeda of Japan appointed director general November 7, 2005
- EU, Japan, Russia, United States, Korea, China, India



- **Opportunities to get involved both in national fusion programs and in ITER**